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FISSION DECAY OF THE ISOSCALAR GIANT QUADRUPOLE RESONANCE IN ^{24}Mg S. LAWITZKI, D. PADE, B. GONSIOR, C.D. UHLHORN ¹*Ruhr-Universität Bochum, D-4630 Bochum, Fed. Rep. Germany*

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The $^{24}\text{Mg}(\alpha, \alpha')^{12}\text{C} + ^{12}\text{C}$ reaction was studied by measuring ^{12}C fragments in coincidence with inelastically scattered α -particles at $E_\alpha = 120$ MeV. Both ^{12}C fragments were identified using the $\Delta E - E$ technique. The measured angular correlations indicate that the $^{12}\text{C}_{\text{gs}} + ^{12}\text{C}_{\text{gs}}$ decay channel is dominated by decay of $L = 2$ strength, which yields an integrated fraction of 0.14% of the E2 EWSR strength in comparison with 22.2% of the E2 EWSR strength observed in singles inelastic α -scattering experiments in the same excitation energy region.

Since the discovery [1] of the intermediate resonance-like structures as a common phenomenon in light heavy-ion systems (see refs. [2,3], and references therein), especially the $^{12}\text{C} + ^{12}\text{C}$ reaction has received great experimental and theoretical attention. In the vicinity of the Coulomb barrier, the excitation functions of various exit channels exhibit a large variety of structures from broad shape-resonances [4] to intermediate structure in the fusion channel [5] and in the inelastic scattering channels [3]. It is not yet clear, whether these structures are to be attributed to entrance channel effects or to compound nuclear states, which serve as "doorway states" for fusion or fission [6].

The dominant isoscalar collective excitation mode of ^{24}Mg in the energy region above the Coulomb barrier of the $^{12}\text{C} + ^{12}\text{C}$ channel ($V_c \approx 6$ MeV $\approx E_x(^{24}\text{Mg}) \approx 20$ MeV) is the isoscalar giant quadrupole resonance (GQR). The particle decay (p and α) of the GQR into light nuclei has been the subject of numerous experiments [7-9], whereas the observation of the decay into heavy fragments suffers from great experimental difficulties and therefore has scarcely been studied

[10,11]. The symmetric fission of ^{24}Mg has been investigated [10] with the (e, ^{12}C) reaction at electron energies $21 \text{ MeV} \leq E_e \leq 40 \text{ MeV}$. Large average fission widths were deduced for $L = 0$ and $L = 2$ excitation [10]. Also in the symmetric fission decay of ^{24}Mg induced by inelastic α -scattering measured at large scattering angles [11] the results possibly indicated large fission widths compared to statistical model predictions. Only in the ^{24}Mg nucleus a large part of the GQR is located at an excitation energy above the threshold plus Coulomb barrier ($-Q + E_c$) for a heavy ion decay channel, which in this case is $^{12}\text{C}_{\text{gs}} + ^{12}\text{C}_{\text{gs}}$. The fusion reaction channel $^{12}\text{C}(^{12}\text{C}, \gamma_0)$ proceeds through states in ^{24}Mg which are of quadrupole nature [5] and should thus be observed in inelastic α -scattering as part of the GQR.

In this letter we report on an investigation of the $^{24}\text{Mg}(\alpha, \alpha')^{12}\text{C} + ^{12}\text{C}$ reaction. The experiments were performed at the AVF cyclotron of the KVI Groningen with a 120 MeV momentum analyzed α -beam. Isotopically enriched (99.7%), self-supporting ^{24}Mg targets [12] with areal densities between $60 \mu\text{g}/\text{cm}^2$ and $150 \mu\text{g}/\text{cm}^2$ were used.

To identify the reaction $^{24}\text{Mg}(\alpha, \alpha')^{12}\text{C} + ^{12}\text{C}$ unambiguously, triple coincidences between the inelastically scattered α -particles and both ^{12}C nuclei were

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measured. The α -particles were detected in the focal plane of the magnetic spectrograph QMG/2 [13] at a scattering angle of $\theta_{\text{lab}} = 7.1^\circ$ which corresponds to a center-of-mass angle of $\theta_{\text{cm}} \approx 8.5^\circ$. This scattering angle which lies near the first maxima of the $J^\pi = 2^+$ and 4^+ angular distributions was chosen to enhance the yield of these multipolarities compared to others. The spectrograph had an opening angle of $\Delta\theta = 2.6^\circ$, $\Delta\phi = 5.6^\circ$ which corresponds to a solid angle $\Delta\Omega = 4.3$ msr. The overall energy resolution achieved for the inelastically scattered α -particles was $\Delta E \leq 70$ keV.

The ^{12}C fragments were detected in the reaction plane with a setup which consisted of two $\Delta E - E$ detector telescopes (tel. 1 and tel. 2), which were placed at three different angle pairs ($\theta_1 = -45^\circ, \theta_2 = 135^\circ$), ($\theta_1 = -70^\circ, \theta_2 = 91^\circ$) and ($\theta_1 = 35^\circ, \theta_2 = -114^\circ$) where the angles are given with respect to the beam axis. The angles at the opposite side of the beam (relative to $\theta_{\alpha'}$) are denoted with a minus sign. These angles correspond (at $E_x(^{24}\text{Mg}) \approx 23$ MeV) to $\theta_{\text{cm}} \approx \theta^\circ, 30^\circ$ and 90° in the center-of-mass coordinate system of the recoiling $^{24}\text{Mg}^*$ nucleus.

To detect and identify the ^{12}C fragments with kinetic energies in the range 1–15 MeV (depending on detection angle and $E_x(^{24}\text{Mg})$), the detector telescopes consisted of ΔE -ionization chambers and E -semiconductor detectors. The telescopes covered solid angles of 7 msr (tel. 1) and 54 msr (tel. 2). In one of the measurements ($\theta_1 = -70^\circ, \theta_2 = 91^\circ$) tel. 2 was replaced by a semiconductor detector telescope (25 μm ΔE -, 2000 μm E -detector) with a solid angle of 64 msr. To minimize the energy loss of the ^{12}C fragments in the target, target angles were chosen such that the directions of the ^{12}C fragments were nearly perpendicular to the target. Coincidences between the focal plane detector of the spectrograph and one or both of the telescopes were recorded on tape event by event as a set of 19 parameters for later off-line analysis.

The differential and double differential cross sections were normalized by comparing measured elastic differential cross sections of the $^{24}\text{Mg}(\alpha, \alpha')^{24}\text{Mg}$ reaction to results of optical model calculations. The uncertainty in the absolute differential cross sections due to this normalization procedure is estimated to be less than 10%.

The analysis of the triple coincidences was done off-line. Complete identification of α -particles was obtained in the focal plane detector. In tel. 1 complete iden-

tification of the ^{12}C particles could be achieved above 3.5 MeV kinetic energy, while at lower energies it was possible to distinguish heavy ions from low-energy α -particles down to 1.5 MeV.

Because of the very low kinetic energies of the carbon fragments in tel. 2, where most of the fragments had energies below the Bragg-maximum of α -particles in the runs with $\theta_{\text{cm}} \approx \theta^\circ$ and 30° , an analysis of the total kinetic energies of all detected particles had to be done in order to prove that each event fulfilled the kinematic conditions for breakup of $^{24}\text{Mg}^*$ into $^{12}\text{C} + ^{12}\text{C}$. In this manner three types of breakup events could be identified: $^{24}\text{Mg}^* \rightarrow ^{12}\text{C}_{\text{gs}} + ^{12}\text{C}_{\text{gs}}$, $^{24}\text{Mg}^* \rightarrow ^{12}\text{C}_{\text{gs}} + ^{12}\text{C}^*(2^+, 4.44 \text{ MeV})$ and $^{24}\text{Mg}^* \rightarrow ^{12}\text{C}^*(2^+, 4.44 \text{ MeV}) + ^{12}\text{C}^*(2^+, 4.44 \text{ MeV})$. Fig. 1 shows the spectra of each exit channel displayed versus $E_x(^{24}\text{Mg})$. Because of the low statistics the events are summed in 200 keV wide energy bins.

The double differential cross sections $d^2\sigma_{\text{cc}}/d\Omega_{\alpha'}$, $d\Omega_{\text{cc}}$ deduced from these data are listed in table 1, together with the average angles for breakup in the center-of-mass system. The errors quoted include only statistical errors except for the experiment at $\theta_{\text{cm}} \approx \theta^\circ$, where an estimated error for background subtraction has been included. All other errors are believed to be small.

We will limit the following discussion to the decay of $^{24}\text{Mg}^*$ into $^{12}\text{C}_{\text{gs}} + ^{12}\text{C}_{\text{gs}}$ because of the rather poor statistics in the other decay channels. In fig. 2, the double differential cross section, summed over the region $E_x = 19\text{--}29$ MeV is plotted versus center-of-mass angle, which is measured with respect to the recoil angle of $^{24}\text{Mg}^*$. The results of angular correlations calculated with the program ANGCOR [14] assuming $J^\pi = 2^+$ and 4^+ intermediate states in ^{24}Mg are shown for comparison. The angular correlations were calculated with m-substate populations obtained from a DWBA calculation [15] with a collective type ($R \text{ d}U/\text{d}r$) form factor. Optical model parameters [16], which have been shown to give a good description of both the elastic and inelastic scattering angular distributions of α -particles from ^{24}Mg , were used.

At the α -scattering angle $\theta_{\alpha'} = 7.1^\circ$ the symmetry axis for the decay of $J^\pi = 2^+$ excited states of ^{24}Mg is rotated by $\approx 30^\circ$ cm with respect to the recoil axis which is the symmetry axis in a plane wave Born approximation. The theoretical prediction for a 2^+ state

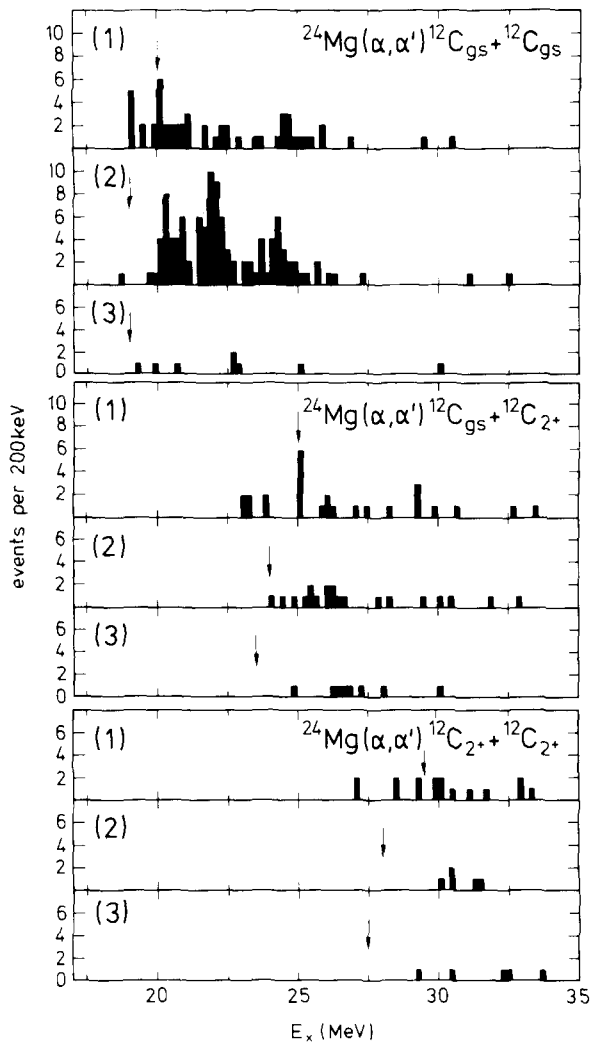


Table 1

Absolute double differential cross sections obtained for the observed decay channels of the $^{24}\text{Mg}(\alpha, \alpha')^{12}\text{C} + ^{12}\text{C}$ reaction. A: $^{24}\text{Mg}(\alpha, \alpha')^{12}\text{C}_{\text{gs}} + ^{12}\text{C}_{\text{gs}}$ for $19 \text{ MeV} \leq E_x(^{24}\text{Mg}) \leq 29 \text{ MeV}$; B: $^{24}\text{Mg}(\alpha, \alpha')^{12}\text{C}_{\text{gs}} + ^{12}\text{C}(2^+, 4.44 \text{ MeV})$ for $22 \text{ MeV} \leq E_x(^{24}\text{Mg}) \leq 32 \text{ MeV}$; C: $^{24}\text{Mg}(\alpha, \alpha')^{12}\text{C}(2^+, 4.44 \text{ MeV}) + ^{12}\text{C}(2^+, 4.44 \text{ MeV})$ for $25 \text{ MeV} \leq E_x(^{24}\text{Mg}) \leq 35 \text{ MeV}$

Type of event	θ_1 [°]	θ_2 [°]	θ_{cm} [°] a)	$d^2\sigma_{\text{cc}}/d\Omega_{\alpha'} d\Omega_{\text{cc}}$ [$\mu\text{b}/\text{sr}^2$]
A	-45	135	-1.8	22.9 ± 4.4
	-70	91	31.3	29.9 ± 3.9
	35	-144	85	4.3 ± 1.9
B	-45	135	5.6	9.6 ± 3.7
	-70	91	38.9	8.2 ± 2.0
	35	-114	85.6	8.1 ± 1.6
C	-45	135	12.5	5.8 ± 2.7
	-70	91	44.8	2.4 ± 1.1
	35	-114	91	4.0 ± 1.8

a) Center-of-mass angles have been averaged over excitation energy and weighted by the measured triple differential cross section.

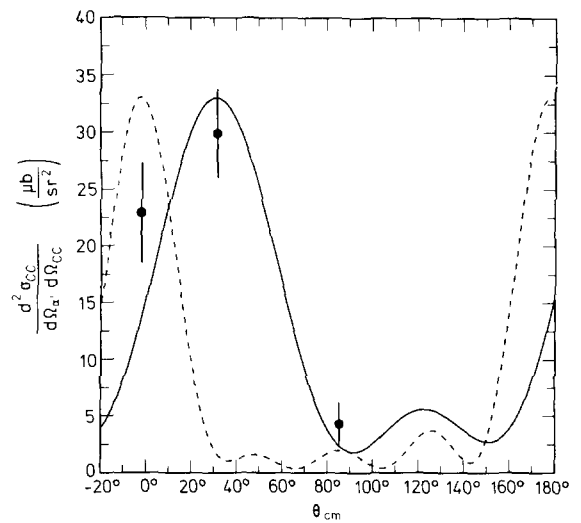


Fig. 2. Double differential cross section $d^2\sigma_{\text{cc}}/d\Omega_{\alpha'}d\Omega_{\text{cc}}$ ($E_x = 19-29 \text{ MeV}$) in comparison with angular correlations [solid line (fitted): $J^\pi = 2^+$, dashed line: $J^\pi = 4^+$] where the m sub-state population amplitudes were obtained from a distorted waves calculation for inelastic α -scattering.

Fig. 1. α -spectra in coincidence with ^{12}C fragments from the reaction $^{24}\text{Mg}(\alpha, \alpha')^{12}\text{C} + ^{12}\text{C}$ at $E_\alpha = 120 \text{ MeV}$, $\theta_{\alpha'} = 7.1^\circ$ for the breakup at three different center-of-mass angles $\theta \approx 0^\circ$ (1), $\theta \approx 30^\circ$ (2) and $\theta \approx 90^\circ$ (3). Different spectra are for different collected charge. The experimental thresholds for the fission decay of ^{24}Mg which are due to the detection thresholds in the carbon detectors are indicated by arrows.

fits the data reasonably well, which indicates, that a sizeable fraction of the excited states of ^{24}Mg at this excitation energy have spins $J^\pi = 2^+$. Small admixtures of higher multipolarities $J^\pi = 4^+$ etc. decaying into the $^{12}\text{C}_{\text{gs}} + ^{12}\text{C}_{\text{gs}}$ channel cannot be excluded.

The double differential cross sections were integrated over 4π assuming the predicted shape of the angular correlations and summing over the excitation energy range of 19–29 MeV. We obtain $d\sigma_{\text{cc}}/d\Omega_\alpha = 46.8 \pm 5 \mu\text{b}/\text{sr}$. To obtain the integrated fraction of the E2 EWSR, DWBA cross sections for $L = 2$ were

calculated in 1 MeV steps for the region 19–29 MeV. The experimental cross sections in 1 MeV bins were compared to these DWBA cross sections. The deformation parameters β_2 obtained in this way were used to determine the $B(\text{E}2)$ -values employing the radial moments of the real part of the optical potential (see further ref. [17]). These $B(\text{E}2)$ -values were integrated as a function of excitation energy to obtain the E2 EWSR. The total integrated cross section between 19–29 MeV thus corresponds to a fraction of 0.14% of the E2 EWSR in the $^{12}\text{C}_{\text{gs}} + ^{12}\text{C}_{\text{gs}}$ channel.

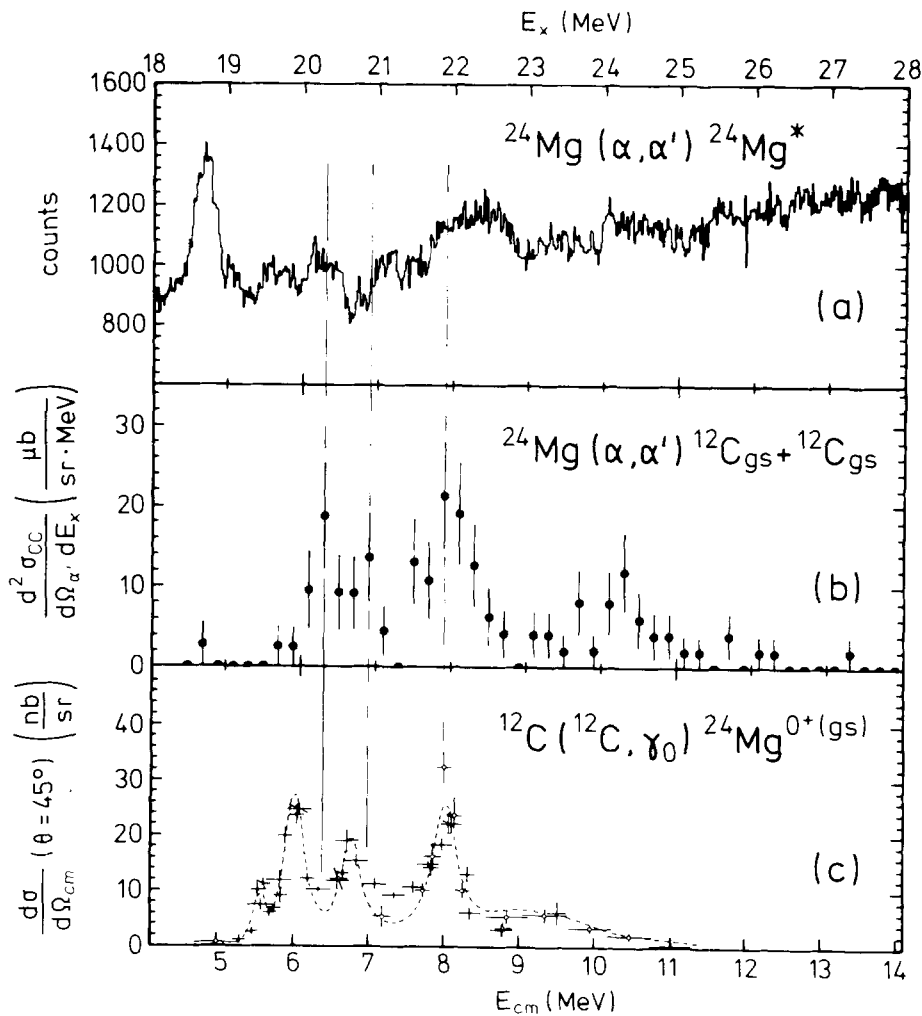


Fig. 3. Comparison of a singles spectrum of inelastically scattered α -particles (a) with inelastic α -scattering followed by symmetric fission into two carbon nuclei in their ground states (b) and the radiative capture cross section for $^{12}\text{C}(^{12}\text{C}, \gamma_0)^{24}\text{Mg}$ (c) of Nathan et al., (ref. [5]).

This is to be compared with a total of 22.2% of the E2 EWSR observed previously by van der Borg et al. [16] in ^{24}Mg in the region of 19.03–26.50 MeV excitation energy.

In fig. 3 the cross section $d^2\sigma_{cc}/d\Omega_\alpha dE_x$ derived from the $\theta_{cm} \approx 30^\circ$ measurement is compared with the singles spectrum for the inelastic scattering of α -particles and the $^{12}\text{C} + ^{12}\text{C}$ radiative capture data of Nathan et al. [5]. There is a clear similarity of the structures in the singles and the coincidence spectra, which have been plotted on the same energy scale. Nearly all structures in the singles spectrum can be found in the coincidence data at the same positions and with comparable widths.

Comparing the coincidence spectrum with the radiative capture cross sections for γ_0 decay, which can be considered as the time-reversed reaction, the similarity of the structure remains, though the peak at $E_x = 20.3$ MeV seems to be observed 260 keV lower in the capture data. We note, however, that this peak appears at exactly the same excitation energy as a quasi-molecular resonance observed by Erb et al. [18]. To a lesser degree the peak at $E_x = 20.9$ MeV is shifted, while the structure at $E_x = 21.9$ MeV is located at the same energy in the fusion and fission channel. The discrepancy between our data and the radiative capture data at the lowest excitation energy in ^{24}Mg , i.e. the resonance at 20.3 MeV, may be related to a difficulty in determining the centroid resonance energy in the radiative capture experiment due to uncertainties in the energy losses of the ^{12}C ions at the lowest bombarding energy.

In conclusion we find strong correlations between the structure of the GQR showing up in the fission decay on the one hand and the $^{12}\text{C}(^{12}\text{C}, \gamma_0)^{24}\text{Mg}$ radiative capture reaction on the other. This emphasizes the role of the GQR as doorway state for fusion and fission [6] and connects the intermediate structure of the radiative capture reaction with collective excita-

tions of the ^{24}Mg nucleus. In a macroscopic view of the GQR as an isoscalar vibrational state, this shows an overlap of the wavefunction of this highly collective state with the symmetric heavy ion channel $^{12}\text{C} + ^{12}\text{C}$.

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References

- [1] D.A. Bromley, J.A. Kühner and E. Almquist, Phys. Rev. Lett. 4 (1960) 365; Phys. Rev. 123 (1961) 878.
- [2] T.M. Cormier, Ann. Rev. Nucl. Part. Sci. 32 (1982) 271.
- [3] S.J. Sanders et al., Phys. Rev. C 31 (1985) 1775.
- [4] D.G. Kovar et al., Phys. Rev. C 20 (1979) 1305.
- [5] A.M. Nathan, A.M. Sandorfi and T.J. Bowles, Phys. Rev. C 24 (1981) 932.
- [6] R.H. Lemmer and C. Toepffer, Phys. Rev. Lett. 44 (1980) 26.
- [7] F. Zwarts et al., Nucl. Phys. A 439 (1985) 117, and references therein.
- [8] K.T. Knöpfle et al., Phys. Rev. Lett. 46 (1981) 1372; Phys. Lett. B 74 (1978) 191.
- [9] D.H. Youngblood et al., Phys. Rev. C 15 (1977) 246.
- [10] A.M. Sandorfi et al., Phys. Rev. Lett. 40 (1978) 1248; 45 (1980) 1615; 38 (1977) 1463.
- [11] J. Wilczynski et al., Nucl. Phys. A 334 (1980) 317.
- [12] B. Hippert, Jahresbericht DTL Bochum, 10 (1983) 5.
- [13] A.G. Drentje, H.A. Enge and S.B. Kowalski, Nucl. Instrum. Methods 122 (1974) 485; J.C. Vermeulen et al., Nucl. Instrum. Methods 180 (1981) 93.
- [14] M.N. Harakeh and L.W. Put, Program ANGCOR, KVI-67i Internal report 1979.
- [15] P.D. Kunz, Program DWUCK4, University of Colorado, unpublished.
- [16] K. van der Borg, M.N. Harakeh and A. van der Woude, Nucl. Phys. A 365 (1981) 241.
- [17] M.N. Harakeh, Program BEL, KVI-77i Internal report 1981; R.S. Mackintosh, Nucl. Phys. A266 (1976) 379.
- [18] K.A. Erb et al., Phys. Rev. C 22 (1980) 507.